

# Polarized Foreground Emission from Dust: Grain Alignment and MHD Turbulence

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## Abstract

Aligned grains present a foreground for cosmic microwave emission studies. We review basic physical processes involved in grain alignment and discuss the niches for different alignment mechanisms. We show that mechanisms which were favored for decades do not look so promising right now, while the radiative torque mechanism ignored for more than 20 years looks quite attractive. We discuss alignment of small rotating grains that are thought to be responsible for 10-90 GHz anomalous foreground and polarization arising from magnetic grains.

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## 1 Introduction

Diffuse Galactic microwave emission carries important information on the fundamental properties of interstellar medium, but it also interferes with the Cosmic Microwave Background (CMB) experiments (see Tegmark et al. 1999 and references therein). Polarization of the CMB provides information about the Universe that is not contained in the temperature data (see Prunet & Lazarian 1999, Davis & Wilkinson 1999) and a number of groups around the world (see Table 1 in Staggs et al. 1999) work hard to determine the CMB polarization. In view of this work, the issue of determining the degree and properties of Galactic foreground polarization becomes vital.

A known source of polarized foreground is thermal emission from aligned grains. Grain alignment of interstellar dust has been discovered more than half a century ago. Hall (1949) and Hiltner (1949) reported polarization that was attributed to the differential extinction of starlight by dust particles with longer axes preferentially aligned. Very soon it was realized that the alignment happens with respect to the interstellar magnetic field<sup>1</sup>.

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<sup>1</sup> The relation between grain alignment direction and that of magnetic field is clear

For many years grain alignment theory had a very limited predictive power and was an issue of hot debates. This caused somewhat cynical approach to the theory among some of the polarimetry practitioners who preferred to be guided in their work by the following rules of thumb: *All grains are always aligned and the alignment happens with the longer grain axes perpendicular to magnetic field*. This simple recipe was shattered, however, by observational data which indicated that

- I. Grains of sizes smaller than the critical size are either not aligned or marginally aligned (Mathis 1986, Kim & Martin 1995).
- II. Carbonaceous grains are not aligned, but silicate grains are aligned (see Mathis 1986).
- III. Substantial part of grains deep within molecular clouds are not aligned (Goodman et al. 1995, Lazarian, Goodman & Myers 1997).
- VI. Grains might be aligned with longer axes parallel to magnetic fields<sup>2</sup> (Rao et al 1998).

A boost of the interest to grain alignment came from the search of Cosmic Microwave Background (CMB) polarization (see Lazarian & Prunet 2002, for a review). Aligned dust in this case acts as a source of a ubiquitous foreground that is necessary to remove from the data. It is clear that understanding of grain alignment is the key element for such a removal. With the present level of interest to the CMB polarization we are bound to have a lot of microwave and far infrared polarimetry data. It is important to understand to what extent this data reflects the structure of magnetic field in the Galaxy and whether this data can be used to get insight into the processes of galactic magnetic field generation and into interstellar turbulence<sup>3</sup>.

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from a comparison of synchrotron polarization maps and those of galactic starlight polarization (see Serkowski, Mathewson & Ford 1975). Recent measurements of polarization in external galaxies (see Jones 2000) makes this relation even more obvious.

<sup>2</sup> A simple, but not always clearly understood property of grain alignment in interstellar medium is that it always happens in respect to magnetic field. It can be shown that the fast (compared with other time scales) Larmor precession of grains makes the magnetic field the reference axis. Note, however, that grains may align with their longer axes *perpendicular* or *parallel* to magnetic field direction. Similarly, magnetic fields may change their configuration and orientation in space (e.g. due to Alfvén waves), but if the time for such a change is much longer than the Larmor period the alignment of grains *in respect to the field lines* persists as the consequence of preservation of the adiabatic invariant.

<sup>3</sup> Velocity and magnetic field statistics provide the most clear insight in what is going on with the turbulence. With velocity statistics available through the recently developed Velocity Channel Analysis (VCA) technique (Lazarian & Pogosyan 2000) magnetic fields statistics is the missing element. Polarized starlight and emission from aligned grains provide the easiest way to get such a statistics.

Alignment of the tiny spinning grains that are thought to be responsible for the microwave emission in the 10-90 GHz is a separate topic that we deal with. We also discuss polarization arising from grains with strong magnetic response and an interpretation of the polarized emission in terms of galactic MHD turbulence.

## 2 Basic Facts: Aligned Grains & Polarized Radiation

### 2.1 Linear Polarized Starlight from Aligned Grains

For an ensemble of aligned grains the extinction perpendicular and parallel to the direction of alignment and parallel are different<sup>4</sup>. Therefore that is initially unpolarized starlight acquires polarization while passing through a volume with aligned grains. If the extinction in the direction of alignment is  $\tau_{\parallel}$  and in the perpendicular direction is  $\tau_{\perp}$  one can write the polarization,  $P_{abs}$ , by selective extinction of grains as

$$P_{abs} = \frac{e^{-\tau_{\parallel}} - e^{-\tau_{\perp}}}{e^{-\tau_{\parallel}} + e^{-\tau_{\perp}}} \approx -(\tau_{\parallel} - \tau_{\perp})/2, \quad (1)$$

where the latter approximation is valid for  $\tau_{\parallel} - \tau_{\perp} \ll 1$ . To relate the difference of extinctions to the properties of aligned grains one can take into account the fact that the extinction is proportional to the product of the grain density and their cross sections. If a cloud is composed of identical aligned grains  $\tau_{\parallel}$  and  $\tau_{\perp}$  are proportional to the number of grains along the light path times the corresponding cross sections, which are, respectively,  $C_{\parallel}$  and  $C_{\perp}$ .

In reality one has to consider additional complications like incomplete grain alignment, and variations in the direction of the alignment axis (in most cases the latter is the direction of magnetic field, as discussed above) along the line of sight. To obtain an adequate description one can (see Roberge & Lazarian 1999) consider an electromagnetic wave propagating along the line of sight  $\hat{\mathbf{z}}^o$  axis. The transfer equations for the Stokes parameters depend on the cross sections,  $C_{xo}$  and  $C_{yo}$ , for linearly polarized waves with the electric vector,  $\mathbf{E}$ , along the  $\hat{\mathbf{x}}^o$  and  $\hat{\mathbf{y}}^o$  directions that are in the plane perpendicular to  $\hat{\mathbf{z}}^o$  (see Lee & Draine 1985).

To calculate  $C_{xo}$  and  $C_{yo}$ , one transforms the components of  $\mathbf{E}$  to a frame aligned with the principal axes of the grain and takes the appropriately-

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<sup>4</sup> According to Hildebrand & Dragovan (1995) the best fit of the grain properties corresponds to oblate grains with the ratio of axis about 2/3.

weighted sum of the cross sections,  $C_{\parallel}$  and  $C_{\perp}$  for  $\mathbf{E}$  polarized along the grain axes (Fig 1b illustrates the geometry of observations). When the transformation is carried out and the resulting expressions are averaged over precession angles, one finds (see transformations in Lee & Draine 1985 for spheroidal grains and in Efrimsky 2002 for a general case) that the mean cross sections are

$$C_{xo} = C_{avg} + \frac{1}{3} R (C_{\perp} - C_{\parallel}) (1 - 3 \cos^2 \zeta) \quad , \quad (2)$$

$$C_{yo} = C_{avg} + \frac{1}{3} R (C_{\perp} - C_{\parallel}) \quad , \quad (3)$$

where  $\zeta$  is the angle between the polarization axis and the  $\hat{\mathbf{x}}^o \hat{\mathbf{y}}^o$  plane;  $C_{avg} \equiv (2C_{\perp} + C_{\parallel})/3$  is the effective cross section for randomly-oriented grains. To characterize the alignment we used in eq. (3) the Rayleigh reduction factor (Greenberg 1968)

$$R \equiv \langle G(\cos^2 \theta) G(\cos^2 \beta) \rangle \quad (4)$$

where angular brackets denote ensemble averaging,  $G(x) \equiv 3/2(x - 1/3)$ ,  $\theta$  is the angle between the axis of the largest moment of inertia (henceforth the axis of maximal inertia) and the magnetic field  $\mathbf{B}$ , while  $\beta$  is the angle between the angular momentum  $\mathbf{J}$  and  $\mathbf{B}$ . To characterize  $\mathbf{J}$  alignment in grain axes and in respect to magnetic field, the measures  $Q_X \equiv \langle G(\theta) \rangle$  and  $Q_J \equiv \langle G(\beta) \rangle$  are used. Unfortunately, these statistics are not independent and therefore  $R$  is not equal to  $Q_J Q_X$  (see Lazarian 1998, Roberge & Lazarian 1999). This considerably complicates the treatment of grain alignment.

## 2.2 Polarized Emission from Aligned Grains

The difference in  $\tau_{\parallel}$  and  $\tau_{\perp}$  results in emission of aligned grains being polarized:

$$P_{em} = \frac{(1 - e^{-\tau_{\parallel}}) - (1 - e^{-\tau_{\perp}})}{(1 - e^{-\tau_{\parallel}}) + (1 - e^{-\tau_{\perp}})} \approx \frac{\tau_{\parallel} - \tau_{\perp}}{\tau_{\parallel} + \tau_{\perp}} \quad , \quad (5)$$

where both the optical depths  $\tau_{\parallel}$  and  $\tau_{\perp}$  were assumed to be small. Taking into account that both  $P_{em}$  and  $P_{abs}$  are functions of wavelength  $\lambda$  and combining eqs.(1) and (6), one gets for  $\tau = (\tau_{\parallel} + \tau_{\perp})/2$

$$P_{em}(\lambda) \approx -P_{abs}(\lambda)/\tau(\lambda) \quad , \quad (6)$$

which establishes the relation between polarization in emission and absorption. The minus sign in eq (6) reflects the fact that emission and absorption polarization are orthogonal. As  $P_{abs}$  depends on  $R$ ,  $P_{em}$  also depends on the Rayleigh reduction factor.

### 3 Grain Alignment Theory: New and Old Ideas

We have seen in the previous sections that both linear and circular polarizations depend on the degree of grain alignment given by  $R$ -factor (4). Therefore it is the goal of grain alignment theory to determine this factor. The complexity of the grain alignment is illustrated in Fig 1, which shows that grain alignment is indeed a multi-stage process.

A number of different mechanisms that produce grain alignment has been developed by now (see table 1 in Lazarian, Goodman & Myers 1997). Dealing with a particular situation one has to identify the dominant alignment process. Therefore it is essential to understand different mechanisms. By now the theory of grain alignment is rather complex. This makes it advantageous to follow the evolution of grain alignment ideas. It is instructive to see the major role that observations played in shaping up of the theory.

#### 3.1 Foundations of the Theory

The first stage of alignment theory development started directly after the discovery of starlight polarization. Nearly simultaneously Davis & Greenstein (1950) and Gold (1951) proposed their scenarios of alignment.

##### *Paramagnetic Alignment: Davis-Greenstein Process*

Davis-Greenstein mechanism (henceforth D-G mechanism) is based on the paramagnetic dissipation that is experienced by a rotating grain. Paramagnetic materials contain unpaired electrons which get oriented by the interstellar magnetic field  $\mathbf{B}$ . The orientation of spins causes grain magnetization and the latter varies as the vector of magnetization rotates in grain body coordinates. This causes paramagnetic losses at the expense of grain rotation energy. Note, that if the grain rotational velocity  $\boldsymbol{\omega}$  is parallel to  $\mathbf{B}$ , the grain magnetization does not change with time and therefore no dissipation takes place. Thus the paramagnetic dissipation acts to decrease the component of  $\boldsymbol{\omega}$  perpendicular to  $\mathbf{B}$  and one may expect that eventually grains will tend to rotate with  $\boldsymbol{\omega} \parallel \mathbf{B}$  provided that the time of relaxation  $t_{D-G}$  is much shorter than  $t_{gas}$ , the time of randomization through chaotic gaseous bombardment. In practice, the last condition is difficult to satisfy. For  $10^{-5}$  cm grains in the

## Simplified Model of Alignment

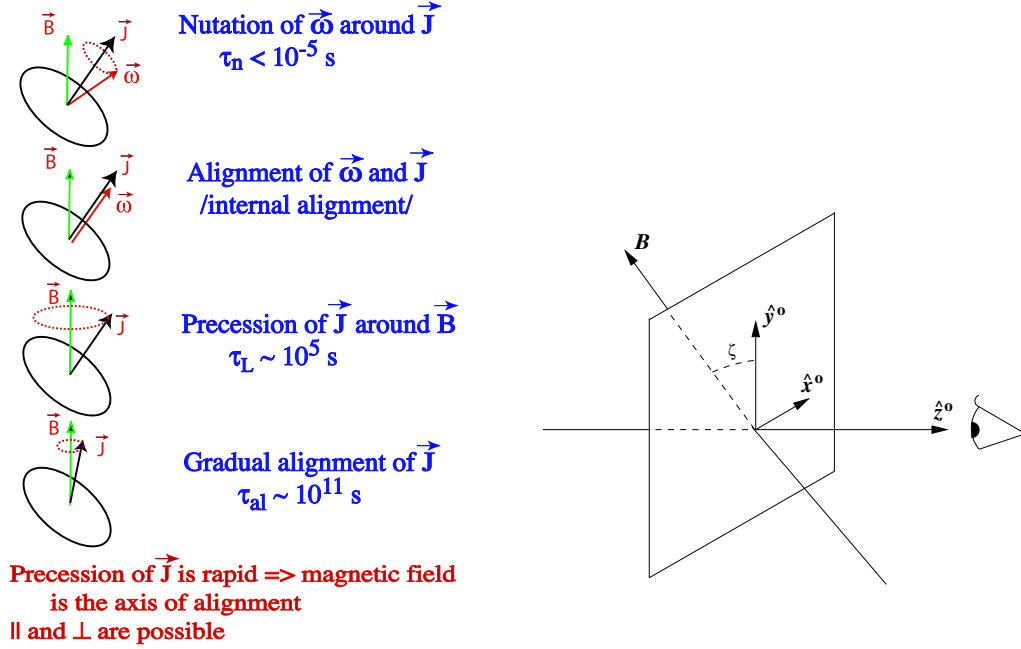


Fig. 1. a) Left panel. Alignment of grains implies several alignment processes acting simultaneously spanning over many scales. Internal alignment was introduced by Purcell (1979) and was assumed to be a slow process. Lazarian & Draine (1999a) showed that the internal alignment is  $10^6$  times faster if nuclear spins are accounted for. The time scale of  $\mathbf{J}$  and  $\mathbf{B}$  alignment is given for diffuse interstellar medium. It is faster in circumstellar regions and for comet dust. b) Right panel. Geometry of observations (after Roberge & Lazarian 1999).

diffuse interstellar medium  $t_{D-G}$  is of the order of  $7 \times 10^{13} a_{(-5)}^2 B_{(5)}^{-2} \text{ s}$ , while  $t_{gas}$  is  $3 \times 10^{12} n_{(20)} T_{(2)}^{-1/2} a_{(-5)} \text{ s}$  ( see table 2 in Lazarian & Draine 1997) if magnetic field is  $5 \times 10^{-6} \text{ G}$  and temperature and density of gas are 100 K and  $20 \text{ cm}^{-3}$ , respectively. However, in view of uncertainties in interstellar parameters the D-G theory initially looked plausible.

### Mechanical Alignment: Gold Process

Gold mechanism is a process of mechanical alignment of grains. Consider a needle-like grain interacting with a stream of atoms. Assuming that collisions are inelastic, it is easy to see that every bombarding atom deposits angular momentum  $\delta \mathbf{J} = m_{atom} \mathbf{r} \times \mathbf{v}_{atom}$  with the grain, which is directed perpendicular to both the needle axis  $\mathbf{r}$  and the velocity of atoms  $\mathbf{v}_{atom}$ . It is obvious that the resulting grain angular momenta will be in the plane perpendicular to the direction of the stream. It is also easy to see that this type of alignment will be efficient only if the flow is supersonic<sup>5</sup>. Thus the main issue with the Gold mechanism is to provide supersonic drift of gas and grains. Gold originally

<sup>5</sup> Otherwise grains will see atoms coming not from one direction, but from a wide cone of directions (see Lazarian 1997a) and the efficiency of alignment will decrease.

proposed collisions between clouds as the means of enabling this drift, but later papers (Davis 1955) showed that the process could only align grains over limited patches of interstellar space, and thus the process cannot account for the ubiquitous grain alignment in diffuse medium.

### *Quantitative Treatment and Enhanced Magnetism*

The first detailed analytical treatment of the problem of D-G alignment was given by Jones & Spitzer (1967) who described the alignment of  $\mathbf{J}$  using a Fokker-Planck equation. This approach allowed them to account for magnetization fluctuations within grain material and thus provided a more accurate picture of  $\mathbf{J}$  alignment.  $Q_X$  was assumed to follow the Maxwellian distribution, although the authors noted that this might not be correct. The first numerical treatment of D-G alignment was presented by Purcell (1969). By that time it became clear that the D-G mechanism is too weak to explain the observed grain alignment. However, Jones & Spitzer (1967) noticed that if interstellar grains contain superparamagnetic, ferro- or ferrimagnetic (henceforth SFM) inclusions<sup>6</sup>, the  $t_{D-G}$  may be reduced by orders of magnitude. Since 10% of atoms in interstellar dust are iron the formation of magnetic clusters in grains was not far fetched (see Spitzer & Turkey 1950, Martin 1995) and therefore the idea was widely accepted. Indeed, with enhanced magnetic susceptibility the D-G mechanism was able to solve all the contemporary problems of alignment. The conclusive at this stage was the paper by Purcell & Spitzer (1971) where all various models of grain alignment, including, for instance, the model of cosmic ray alignment by Salpeter & Wickramasinha (1969) and photon alignment by Harwit (1970) were quantitatively discussed and the D-G model with enhanced magnetism was endorsed. It is this stage of development that is widely reflected in many textbooks.

## *3.2 Additional Essential Physics*

### *Barnett Effect and Fast Larmor Precession*

It was realized by Martin (1971) that rotating charged grains will develop magnetic moment and the interaction of this moment with the interstellar magnetic field will result in grain precession. The characteristic time for the precession was found to be comparable with  $t_{gas}$ . However, soon a process that renders much larger magnetic moment was discovered (Dolginov & Mytrophanov 1976). This process is the Barnett effect, which is converse of the Einstein-de Haas effect. If in Einstein-de Haas effect a paramagnetic body starts rotating during remagnetizations as its flipping electrons transfer the angular momentum (associated with their spins) to the lattice, in the Barnett

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<sup>6</sup> The evidence for such inclusions was found much later through the study of interstellar dust particles captured in the atmosphere (Bradley 1994).

effect the rotating body shares its angular momentum with the electron subsystem causing magnetization. The magnetization is directed along the grain angular velocity and the value of the Barnett-induced magnetic moment is  $\mu \approx 10^{-19} \omega_{(5)} \text{ erg gauss}^{-1}$  (where  $\omega_{(5)} \equiv \omega/10^5 \text{ s}^{-1}$ ). Therefore the Larmor precession has a period  $t_{Lar} \approx 3 \times 10^6 B_{(5)}^{-1} \text{ s}$  and the magnetic field defines the axis of alignment as we explained in section 1.

#### *Suprathermal Paramagnetic Alignment: Purcell Mechanism*

The next step was done by Purcell(1975, 1979), who discovered that grains can rotate much faster than were previously thought. He noted that variations of photoelectric yield, the  $\text{H}_2$  formation efficiency, and variations of accommodation coefficient over grain surface would result in uncompensated torques acting upon a grain. The  $\text{H}_2$  formation on the grain surface clearly illustrates the process we talk about: if  $\text{H}_2$  formation takes place only over particular catalytic sites, these sites act as miniature rocket engines spinning up the grain. Under such uncompensated torques the grain will spin-up to velocities much higher than thermal (Brownian) and Purcell termed those velocities “suprathermal”. Purcell also noticed that for suprathermally rotating grains internal relaxation will bring  $\mathbf{J}$  parallel to the axis of maximal inertia (i.e.  $Q_X = 1$ ). Indeed, for an oblate spheroidal grain with angular momentum  $\mathbf{J}$  the energy can be written

$$E(\theta) = \frac{J^2}{I_{max}} \left( 1 + \sin^2 \theta (h - 1) \right) \quad (7)$$

where  $h = I_{max}/I_{\perp}$  is the ratio of the maximal to minimal moments of inertia. Internal forces cannot change the angular momentum, but it is evident from Eq. (7) that the energy can be decreased by aligning the axis of maximal inertia along  $\mathbf{J}$ , i.e. decreasing  $\theta$ . Purcell (1979) discusses two possible causes of internal dissipation, the first one related to the well known inelastic relaxation, the second is due to the mechanism that he discovered and termed “Barnett relaxation”. This process may be easily understood. We know that a freely rotating grain preserves the direction of  $\mathbf{J}$ , while angular velocity precesses about  $\mathbf{J}$  and in grain body axes. We learned earlier that the Barnett effect results in the magnetization vector parallel to  $\boldsymbol{\omega}$ . As a result, the Barnett magnetization will precess in body axes and cause paramagnetic relaxation. The “Barnett equivalent magnetic field”, i.e. the equivalent external magnetic field that would cause the same magnetization of the grain material, is  $H_{BE} = 5.6 \times 10^{-3} \omega_{(5)} \text{ G}$ , which is much larger than the interstellar magnetic field. Therefore the Barnett relaxation happens on the scale  $t_{Bar} \approx 4 \times 10^7 \omega_{(5)}^{-2} \text{ sec}$ , i.e. essentially instantly compared to  $t_{gas}$  and  $t_{D-G}$ .

#### *Theory of Crossovers*

If  $Q_X = 1$  and the suprathermally rotating grains are immune to randomization by gaseous bombardment, will paramagnetic grains be perfectly aligned



with  $R = 1$ ? This question was addressed by Spitzer & McGlynn (1979) (henceforth SM79) who observed that adsorption of heavy elements on a grain should result in the resurfacing phenomenon that, e.g. should remove early sites of  $H_2$  formation and create new ones. As the result,  $H_2$  torques will occasionally change their direction and spin the grain down. SM79 showed that in the absence of random torques the spinning down grain will flip over preserving the direction of its original angular momentum. However, in the presence of random torques this direction will be altered with the maximal deviation inflicted over a short period of time just before and after the flip, i.e. during the time when the value of grain angular momentum is minimal. The actual value of angular momentum during this critical period depends on the ability of  $\mathbf{J}$  to deviate from the axis of maximal inertia. SM79 observed that as the Barnett relaxation couples  $\mathbf{J}$  with the axis of maximal inertia it makes randomization of grains during crossover nearly complete. With the resurfacing time  $t_{res}$  estimated by SM79 to be of the order of  $t_{gas}$ , the gain of the alignment efficiency was insufficient to reconcile the theory and observations unless the grains had SFM inclusions.

### *Radiative Torques*

If the introduction of the concept of suprathermality by Purcell changed the way researchers thought of grain dynamics, the introduction of radiative torques passed essentially unnoticed. Dolginov (1972) argued that quartz grains may be spun up due to their specific rotation of polarization while later Dolginov & Mytrophanov (1976) discovered that irregular grain shape may allow grains scatter left and right hand polarized light differentially, thus spinning up helical grains through scattering of photons<sup>7</sup>. They stressed that the most efficient spin-up is expected when grains size is comparable with the wavelength and estimated the torque efficiency for particular helical grain shapes, but failed to provide estimates of the relative efficiency of the mechanism in the standard interstellar conditions. In any case, this ingenious idea had not been appreciated for another 20 years.

### *Observational tests: Serkowski Law*

All in all, by the end of seventies the the following alignment mechanisms were known: 1. paramagnetic( a. with SFM inclusions, b. with suprathermal rotation), 2. mechanical, 3. radiative torques. The third was ignored, the second was believed to be suppressed for suprathermally rotating grains, which left the two modifications of the paramagnetic mechanism as competing alter-

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<sup>7</sup> The principal difference between radiative torque mechanism and the radiative emission/absorption mechanism proposed by Harwit (1970) is that the radiative torques are regular and therefore increase the grain velocity in proportion to time. Harwit's mechanism, on the other hand, is based on stochastic spin-up and therefore is subdominant. We also note that the emission of photons is insensitive to grain helicity as the emitted photons have wavelengths much larger than the grain size.

natives. Mathis (1986) noticed that the interstellar polarization-wavelength dependence known as the Serkowski law (Serkowski et al. 1975) can be explained if grains larger than  $\sim 10^{-5}$  cm are aligned, while smaller grains are not. To account for this behavior Mathis (1986) noticed that the SFM inclusions will have a better chance to be in larger rather than smaller grains. The success of fitting observational data persuaded the researchers that the problem of grain alignment is solved at last.

### 3.3 *Present Stage of Grain Alignment Theory*

Optical and near infrared observations by Goodman et al. (1995) showed that polarization efficiency may drop within dark clouds while far infrared observations by Hildebrand et al. (1984), Hildebrand et al. (1990) revealing aligned grains within star-forming dark clouds. This renewed interest to grain alignment problem.

#### *New Life of Radiative Torques*

Probably the most dramatic change of the picture was the unexpected advent of radiative torques. Before Bruce Draine realized that the torques can be treated with the versatile discrete dipole approximation (DDA) code (Draine & Flatau 1994), their role was unclear. For instance, earlier on difficulties associated with the analytical approach to the problem were discussed in Lazarian (1995a). However, very soon after that Draine (1996) modified the DDA code to calculate the torques acting on grains of arbitrary shape. His work revolutionized the field! The magnitude of torques were found to be substantial and present for grains of various irregular shape (Draine 1996, Draine & Weingartner 1996). After that it became impossible to ignore these torques. Being related to grain shape, rather than surface these torques are long-lived<sup>8</sup>, i.e.  $t_{spin-up} \gg t_{gas}$ , which allowed Draine & Weingartner (1996) to conclude that in the presence of isotropic radiation the radiative torques can support fast grain rotation long enough in order for paramagnetic torques to align grains (and without any SFM inclusions). However, the important question was what would happen in the presence of anisotropic radiation. Indeed, in the presence of such radiation the torques will change as the grain aligns and this may result in a spin-down. Moreover, anisotropic flux of radiation will deposit angular momentum which is likely to overwhelm rather weak paramagnetic torques. These sort of questions were addressed by Draine & Weingartner (1997) and it was found that for most of the tried grain shapes the torques tend to align **J** along magnetic field. The reason for that is yet unclear and some caution

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<sup>8</sup> In the case of the Purcell's rockets the duration of torque action is limited by the time of resurfacing, while in the case of radiative torques it is the time scale on which the grain is either destroyed via collisions, coagulates with another grain or gets a different shape in the process of growth.

is needed as the existing treatment ignores the dynamics of crossovers which is very important for the alignment of suprathermally rotating grains. Nevertheless, radiative torques are extremely appealing as their predictions are consistent with observational data (see Lazarian, Goodman & Myers 1994, Hildebrand et al. 1999, see section 4 as well).

### *New Elements of Crossovers*

Another unexpected development was a substantial change of the picture of crossovers. As we pointed out earlier, Purcell’s discovery of fast internal dissipation resulted in a notion that  $\mathbf{J}$  should always stay along the axis of maximal inertia as long as  $t_{dis} \ll t_{gas}$ . Calculations in SM79 were based on this notion. However, this perfect coupling was questioned in Lazarian (1994) (henceforth L94), where it was shown that thermal fluctuations within grain material partially randomize the distribution of grain axes in respect to  $\mathbf{J}$ . The process was quantified in Lazarian & Roberge (1997) (henceforth LR97), where the distribution of  $\theta$  for a freely rotating grain was defined through the Boltzmann distribution  $\exp(-E(\theta)/kT_{grain})$ , where the energy  $E(\theta)$  is given by Eq. (7). This finding changed the understanding of crossovers a lot. First of all, Lazarian & Draine (1997) (henceforth LD97) observed that thermal fluctuations partially decouple  $\mathbf{J}$  and the axis of maximal inertia and therefore the value of angular momentum at the moment of a flip is substantially larger than SM79 assumed. Thus the randomization during a crossover is reduced and LD97 obtained a nearly perfect alignment for interstellar grains rotating suprathermally, provided that the grains were larger than a certain critical size  $a_c$ . The latter size was found by equating the time of the crossover and the time of the internal dissipation  $t_{dis}$ . For  $a < a_c$  Lazarian & Draine (1999a) found new physical effects, which they termed “thermal flipping” and “thermal trapping”. The thermal flipping takes place as the time of the crossover becomes larger than  $t_{dis}$ . In this situation thermal fluctuations will enable flipovers. However, being random, thermal fluctuations are likely to produce not a single flipover, but multiple ones. As the grain flips back and forth the regular (e.g.  $H_2$ ) torques average out and the grain can spend a lot of time rotating with thermal velocity, i.e. being “thermally trapped”. The paramagnetic alignment of grains rotating with thermal velocities is small (see above) and therefore grains with  $a < a_c$  are expected to be marginally aligned. The picture of preferential alignment of large grains, as we know, corresponds to the Serkowski law and therefore the real issue is to find the value of  $a_c$ . The Barnett relaxation<sup>9</sup> provides a comforting value of  $a_c \sim 10^{-5}$  cm. However, in a recent paper Lazarian & Draine (1999b) reported a new solid state effect that they termed “nuclear relaxation”. This is an analog of Barnett relaxation

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<sup>9</sup> A study by Lazarian & Efroimsky (1999) corrected the earlier estimate by Purcell (1979), but left the conclusion about the Barnett relaxation dominance, and therefore the value of  $a_c$ , intact. For larger objects, e.g. for asteroids, comets, the inelastic relation is dominant (Efroimsky & Lazarian 2000, Efroimsky 2001).

effect that deals with nuclei. Similarly to unpaired electrons nuclei tend to get oriented in a rotating body. However the nuclear analog of “Barnett equivalent” magnetic field is much larger and Lazarian & Draine (1999b) concluded that the nuclear relaxation can be a million times faster than the Barnett relaxation. If this is true  $a_c$  becomes of the order  $10^{-4}$  cm, which means that the majority of interstellar grains undergo constant flipping and rotate essentially thermally in spite of the presence of uncompensated Purcell torques. The radiative torques are not fixed in body coordinates and it is likely that they can provide a means for suprathermal rotation for grains that are larger than the wavelength of the incoming radiation. Naturally, it is of utmost importance to incorporate the theory of crossovers into the existing codes, and this work is under way.

### *New Ideas and Quantitative Theories*

An interest to grain alignment resulted in search of new mechanisms. For instance, Sorrell (1995a,b) proposed a mechanism of grain spin-up due to interaction with cosmic rays that locally heat grains and provide evaporation of adsorbed  $H_2$  molecules. However, detailed calculations in Lazarian & Roberge (1997b) showed that the efficiency of the torques was overestimated; the observations (Chrysostomou et al. 1996) did not confirm Sorrell’s predictions either. A more promising idea that ambipolar diffusion can align interstellar grains was put forward in Roberge & Hanany (1990) (calculations are done in Roberge et al. 1995). Within this mechanism ambipolar drift provides the supersonic velocities necessary for mechanical alignment. Independently L94 proposed a mechanism of mechanical grain alignment using Alfvén waves. Unlike the ambipolar diffusion, this mechanism operates even in ideal MHD and relies only on the difference in inertia of atoms and grains and on the direct interaction of grains with fluctuating magnetic field (Lazarian & Yan 2002, Yan & Lazarian 2002). An additional boost to interest to mechanical processes was gained when it was shown that suprathermally rotating grains can be aligned mechanically (Lazarian 1995a; Lazarian & Efrimsky 1996; Lazarian, Efrimsky & Ozik 1996; Efrimsky 2002). As it was realized that thermally rotating grains do not  $\mathbf{J}$  tightly coupled with the axis of maximal inertia (L94) and the effect was quantified (LR97), it got possible to formulate quantitative theories of Gold (Lazarian 1997a) and Davis-Greenstein (Lazarian 1997b, Roberge & Lazarian 1999) alignments. Together with a better understanding of grain superparamagnetism (Draine & Lazarian 1998a), damping of grain rotation (Draine & Lazarian 1998b) and resurfacing of grains (Lazarian 1995c), these developments increased the predictive power of the grain alignment theory.

## 4 Polarization of Spinning Grain Emission

All the studies above dealt with classical “large” grains. What about very small (e.g.  $a < 10^{-7}$  cm) grains? Can they be aligned? The answer to this question became acute after Draine & Lazarian (1998a,b) explained the anomalous galactic emission in the range 10 – 100 GHz as arising from rapidly (but thermally!) spinning tiny grains. This rotational dipole emission will be polarized if grains are aligned.

Microwave emission from spinning grains is expected to be polarized if grains are aligned. Alignment of ultrasmall grains which are essentially large molecules is likely to be different from alignment of large (i.e.  $a > 10^{-6}$  cm) grains for which the theory of grain alignment (see review by Lazarian 2000) has been developed.

One of the mechanisms that might produce alignment of the ultrasmall grains is the paramagnetic dissipation mechanism suggested half a century ago by Davis and Greenstein (1951) as a means of explaining the polarization of starlight. The Davis-Greenstein alignment mechanism is straightforward: for a spinning grain the component of interstellar magnetic field perpendicular to the grain angular velocity varies in grain coordinates, resulting in time-dependent magnetization, associated energy dissipation, and a torque acting on the grain. As a result grains tend to rotate with angular momenta parallel to the interstellar magnetic field.

Are the ultrasmall grains paramagnetic? The answer to this question is positive owing to the presence of free radicals, paramagnetic carbon rings (see Altshuler & Kozyrev 1964) and captured ions. For paramagnetic grains, the alignment time-scale  $\tau \approx 10^4 \text{ yr } (a/10^{-6} \text{ cm})^2 (10^{-13} \text{ s/K})$  with  $K(\omega) \equiv \text{Im}(\chi)/\omega$ , where  $\omega$  is the angular rotational velocity and  $\chi(\omega)$  is the magnetic susceptibility. The characteristic time of grain magnetic response is the electron precession time in the field of its neighbors, which is also called spin-spin relaxation time and is denoted  $\tau_2$ . If  $\omega \leq \tau_2^{-1} \sim 10^8 \text{ s}^{-1}$ , normal materials at  $T \approx 20 \text{ K}$  have  $K \approx 10^{-13} \text{ s}$ . For higher frequencies, however,  $K(\omega)$  begins to decrease rapidly (Draine & Lazarian 1999, henceforth DL99). As discussed earlier spinning grains must rotate much faster to account for the Foreground X, thus apparently calling into question the efficacy of alignment by paramagnetic dissipation.

Lazarian & Draine (2000, henceforth LD00) found that the traditional picture of paramagnetic relaxation is incomplete, since it disregards the splitting of energy levels within a rotating body. Unpaired electrons spin parallel and antiparallel to the grain angular velocity have different energies causing the so-called “Barnett magnetization” (Landau & Lifshitz 1960). The Barnett

effect, the inverse of the Einstein-De Haas effect, consists of the spontaneous magnetization of a paramagnetic body rotating in field-free space. This effect can be understood in terms of the lattice sharing part of its angular momentum with the spin system. Therefore the implicit assumption in Davis & Greenstein (1951)– that the magnetization within a *rotating grain* in a *static* magnetic field is equivalent to the magnetization within a *stationary grain* in a *rotating* magnetic field – is clearly not exact.

If electrons within a rotating grain are treated as nearly free, the magnetization of the grain is the same for a stationary grain in a “Barnett- equivalent” magnetic field directed along the grain angular velocity  $\omega$  and having an amplitude  $H_{BE} = \hbar\omega/(g\mu_B)$ , where  $g$  is the electron gyromagnetic ratio  $\approx 2$  and  $\mu_B$  is the Bohr magneton. In these conditions the component of magnetic field perpendicular to  $\omega$  causes electron spin resonance (see Athertson 1973).

LD00 called the process of paramagnetic relaxation within a rotating body “resonance relaxation” as opposed to Davis-Greenstein relaxation that disregards the spontaneous magnetization of a rotating body. Solving the Bloch equations (Bloch 1946) LD00 obtained the following expression for the imaginary part of the grain paramagnetic susceptibility (the part responsible for dissipation and therefore alignment):

$$Im(\chi) = \chi_0 \frac{\omega\tau_2}{1 + \gamma^2 g^2 \tau_1 \tau_2 H_1^2} \quad , \quad (8)$$

where  $\gamma \equiv e/2m_e c = 8.8 \times 10^6 \text{ s}^{-1}\text{G}^{-1}$ ,  $\tau_1$  is the spin-lattice relaxation time, and  $H_1$  is interstellar magnetic field intensity. Unlike the corresponding expression in Davis-Greenstein theory, eq. (1) does not vanish for  $\omega$  much larger than the spin-spin relaxation time  $\tau_2$ . The saturation, however, depends on the value of  $H_1$  and  $\tau_1$ . The latter parameter was calculated in LD00 using Raman scattering of phonons, but the calculations are based on the so-called Waller theory, which is known to overestimate  $\tau_1$  considerably. Thus laboratory measurements of relaxation within isolated grains are required.

Fig. 2 shows the predictions of the resonance relaxation mechanism for cold interstellar gas assuming that the spin-lattice relaxation is fast. The discontinuity at  $\sim 20$  GHz is due to the assumption that smaller grains are planar, and larger grains are spherical. The microwave emission will be polarized in the plane perpendicular to magnetic field. The dipole rotational emission predicted in DL98a,b is sufficiently strong that polarization of a few percent may interfere with efforts to measure the polarization of the CMB.

Can we check the alignment of ultrasmall grains via infrared polarimetry? The answer to this question is “probably not”. Indeed, as discussed earlier, infrared emission from ultrasmall grains, e.g.  $12 \mu\text{m}$  emission, takes place as grains ab-

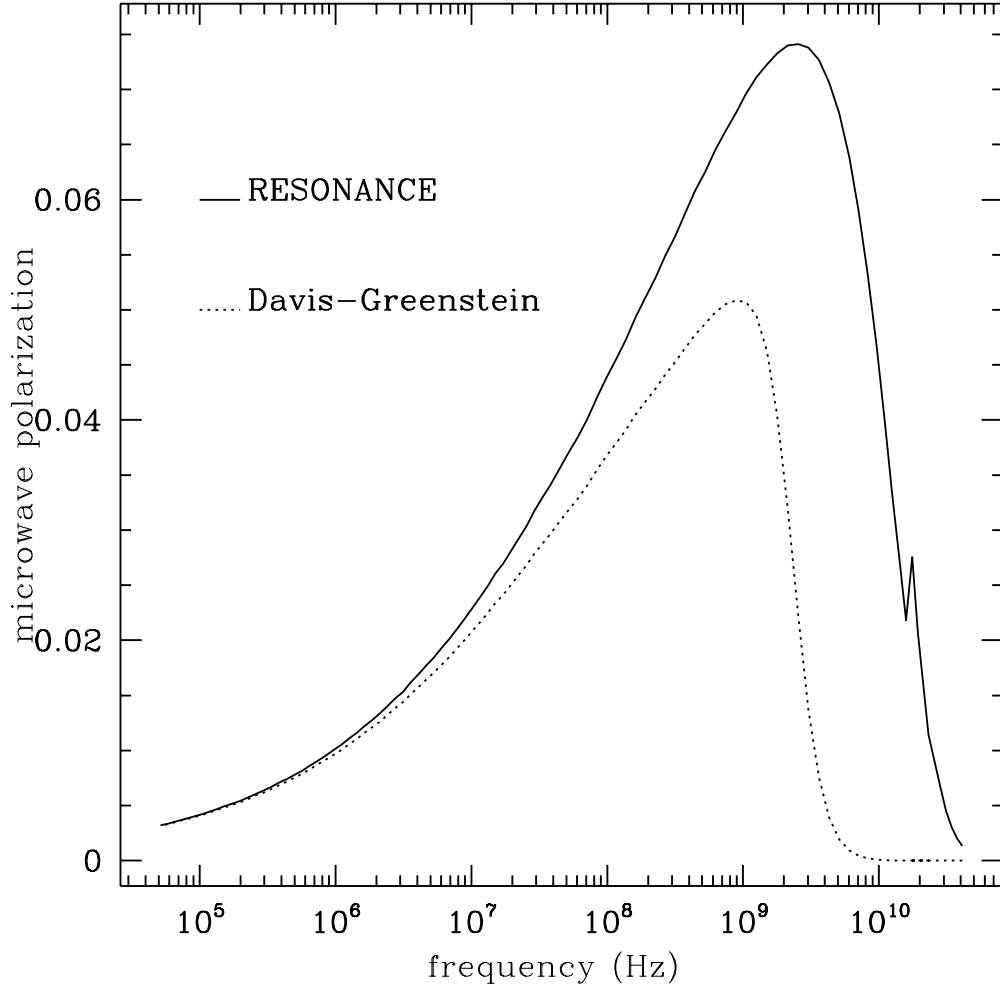


Fig. 2. Measure of grain alignment for both resonance relaxation and Davis-Greenstein relaxation for grains in the cold interstellar medium as a function of frequency (from LD00). For resonance relaxation the saturation effects (see eq. (1)) are neglected, which means that the upper curves correspond to the *maximal* values allowed by the paramagnetic mechanism.

sorb UV photons. These photons raise grain temperature, randomizing grain axes in relation to its angular momentum (see Lazarian & Roberge 1997). Taking values for Barnett relaxation from Lazarian & Draine (1999a), we get the randomization time of the  $10^{-7}$  cm grain to be  $2 \times 10^{-6}$  s, which is less than grain cooling time. As the result, the emanating infrared radiation will be polarized very marginally. If, however, Barnett relaxation is suppressed, the randomization time is determined by inelastic relaxation (Lazarian & Efroimsky 1999) and is  $\sim 0.1$  s, which would entail a partial polarization of infrared emission.

## 5 Polarization of Magneto-Dipole Emission

While the spinning grain hypothesis got recognition in the community, the magnetic dipole emission model suggested by Draine & Lazarian (DL99) was left essentially unnoticed. This is unfortunate, as magnetic dipole emission provides a possible alternative explanation to the Foreground X. Magnetic dipole emission is negligible at optical and infrared frequencies. However, when the frequency of the oscillating magnetic field approaches the precession frequency of electron spin in the field of its neighbors, i.e. 10 GHz, the magneto dipole emissivity becomes substantial.

How likely is that grains are strongly magnetic? Iron is the fifth most abundant element by mass and it is well known that it resides in dust grains (see Savage & Sembach 1996). If 30% of grain mass is carbonaceous, Fe and Ni contribute approximately 30% of the remaining grain mass. Magnetic inclusions are widely discussed in grain alignment literature (Jones & Spitzer 1967, Mathis 1986, Martin 1995, Goodman & Whittet 1995). If a substantial part of this material is ferromagnetic or ferrimagnetic, the magneto-dipole emission can be comparable to that of spinning grains. Indeed, calculations in DL99 showed that less than 5% of interstellar Fe in the form of metallic grains or inclusions is necessary to account for the Foreground X at 90 GHz, while magnetite, i.e.  $\text{Fe}_3\text{O}_4$ , can account for a considerable part of the anomalous emissivity over the whole range of frequencies from 10 to 90 GHz.

The mechanisms of producing polarized magneto-dipole emission is similar to that producing polarization of electro-dipole thermal emission emitted from aligned non-spherical grains (see Hildebrand 1988). There are two significant differences, however. First, strongly magnetic grains can contain just a single magnetic domain. Further magnetization along the axis of this domain is not possible and therefore the magnetic permeability of the grains gets anisotropic:  $\mu = 1$  along the domain axis, and  $\mu = \mu_{\perp}$  for a perpendicular direction. Second, even if a grain contains tiny magnetic inclusions and can be characterized by isotropic permeability, polarization that it produces is orthogonal to the electro-dipole radiation emanating through electro-dipole vibrational emission. In case of the electro-dipole emission, the longer grain axis defines the vector of the electric field, while it defines the vector of the magnetic field in case of magneto-dipole emission.

The results of calculations for single domain iron particle (longer axis coincides with the domain axis) and a grain with metallic Fe inclusions are shown in Fig. 3. Grains are approximated by ellipsoids  $a_1 < a_2 < a_3$  with  $\mathbf{a}_1$  perfectly aligned parallel to the interstellar magnetic field  $\mathbf{B}$ . The polarization is taken to be positive when the electric vector of emitted radiation is perpendicular to  $\mathbf{B}$ ; the latter is the case for electro-dipole radiation of aligned grains. This is



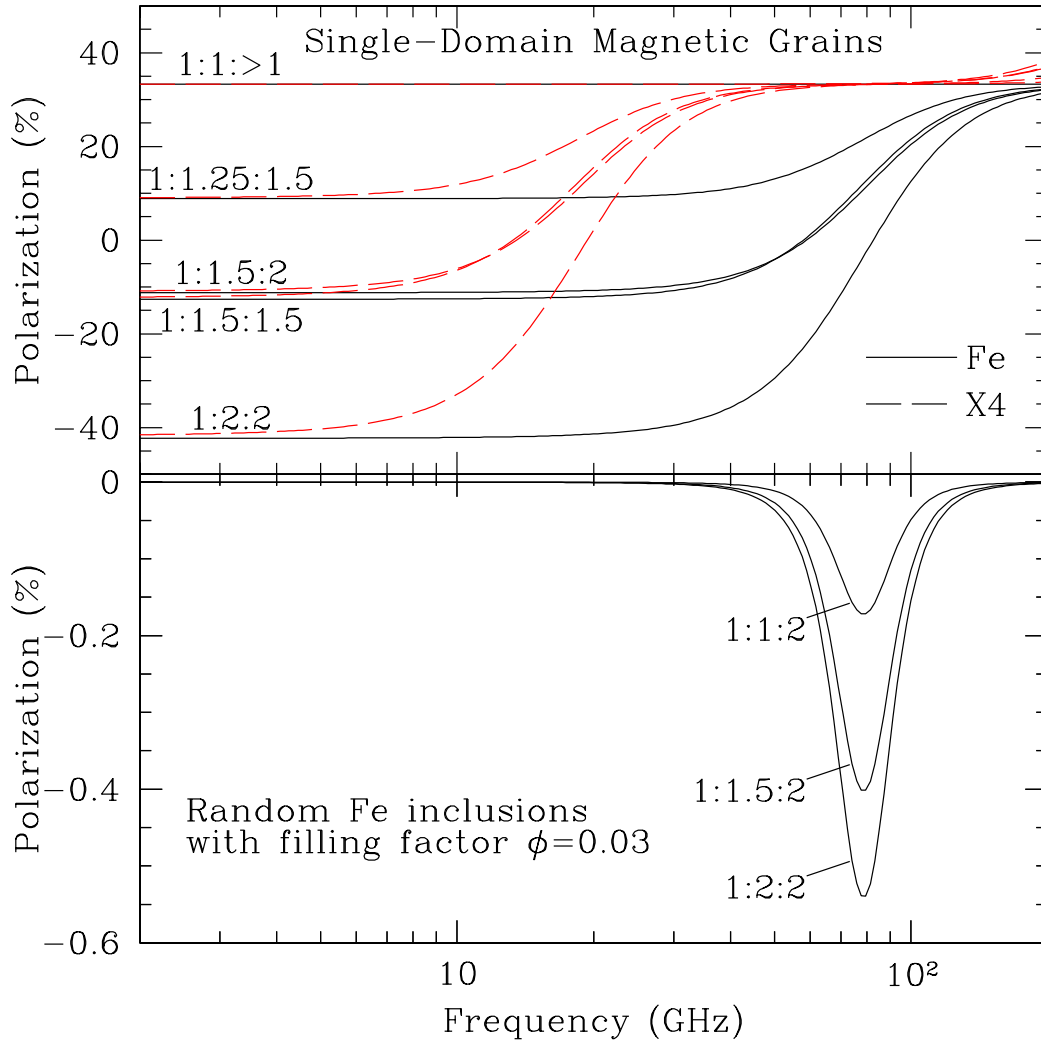


Fig. 3. Polarization from magnetic grains (from DL99). Upper panel: Polarization of thermal emission from perfectly aligned single domain grains of metallic Fe (solid lines) or hypothetical magnetic material that can account for the Foreground X (broken lines). Lower panel: Polarization from perfectly aligned grains with Fe inclusions (filling factor is 0.03). Grains are ellipsoidal and the result are shown for various axial ratios.

also true (see Fig. 3) for high frequency radiation from single dipole grains. It is easy to see why this happens. For high frequencies  $|\mu_{\perp} - 1|^2 \ll 1$  and grain shape factors are unimportant. The only important thing is that the magnetic fluctuations happen perpendicular to  $\mathbf{a}_1$ . With  $\mathbf{a}_1$  parallel to  $\mathbf{B}$ , the electric fluctuations tend to be perpendicular to  $\mathbf{B}$  which explains the polarization of single domain grain being positive. For lower frequencies magnetic fluctuations tend to happen parallel to the intermediate size axis  $\mathbf{a}_2$ . As the grain rotates about  $\mathbf{a}_1 \parallel \mathbf{B}$ , the intensity in a given direction reaches maximum when an observer sees the  $\mathbf{a}_1 \mathbf{a}_2$  grain cross section. Applying earlier arguments it is easy to see that magnetic fluctuations are parallel to  $\mathbf{a}_2$  and therefore for

sufficiently large  $a_2/a_1$  ratio the polarization is negative. *The variation of the polarization direction with frequency presents the characteristic signature of magneto-dipole emission from aligned single-dipole grains and it can be used to separate this component from the CMB signal.* Note that the degree of polarization is large, and such grains may substantially interfere with the attempts of CMB polarimetry. Even if the intensity of magneto-dipole emission is subdominant to that from rotating grains, it can still be quite important in terms of polarization. A relatively weak polarization response is expected for grains with magnetic inclusions (see Fig. 3). The resulting emission is negative as magnetic fluctuations are stronger along longer grain axes, while the short axis is aligned with  $\mathbf{B}$ .

## 6 Polarized Emission from the Galaxy

Attempts to determine the statistics of intensity and polarization fluctuations of cosmic microwave background (CMB) renewed interest to the fluctuations of Galactic foreground radiation (see Tegmark et al. 2000). Angular power spectra of intensity of synchrotron emission and synchrotron polarization (see papers in de Oliveira-Costa & Tegmark 1999) as well as starlight polarization (Fosalba et al. 2002; henceforth FLPT) have been measured. Those measurements revealed a range of power-laws.<sup>10</sup>

Interstellar medium is turbulent and Kolmogorov-type spectra ( $E_{3D}(k) \sim k^{-11/3}$ ,  $k$ =wave number) were reported on the scales from several AU to several kpc (see Armstrong, Rickett, & Spangler 1995; Lazarian & Pogosyan 2000; Stanimirovic & Lazarian 2001). Therefore it is natural to think of the turbulence as the origin of the fluctuations of the diffuse foreground radiation. Interstellar medium is magnetized with magnetic field making turbulence anisotropic. Recent developments on MHD turbulence can be found in Goldreich & Sridhar (1995), Lithwick & Goldreich (2001), and Cho & Lazarian (2002a). See also a review Cho, Lazarian & Vishniac (2002).

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<sup>10</sup> It is customary for CMB studies to expand the foreground intensity over spherical harmonics  $Y_{lm}$ ,  $I(\theta, \phi) = \sum_{l,m} a_{lm} Y_{lm}(\theta, \phi)$ , and write the spectrum in terms of  $C_l \equiv \sum_{m=-l}^{m=l} |a_{lm}|^2 / (2l+1)$ . The measurements indicate that angular power spectrum ( $C_l$ ) of the Galactic emission follows power law ( $C_l \propto l^{-\alpha}$ ) (see FLPT). The multipole moment  $l$  is related to the angular scale  $\theta$  on the sky as  $l \sim \pi/\theta^{radian}$  (or  $l \sim 180^\circ/\theta^\circ$ ). When the angular size of the observed sky patch ( $\Delta\theta \times \Delta\theta$  in radian) is small,  $C_l$  is approximately the ‘energy’ spectrum of fluctuations (Bond & Efstathiou 1987). It is this power spectrum expressed in terms of wavenumber  $k$  ( $\sim l \Delta\theta/\pi$ ) that is usually dealt with in studies of astrophysical turbulence (e.g. Stanimirovic & Lazarian 2001).

The polarization of starlight and of the Far-Infrared Radiation (FIR) from aligned dust grains is affected by the ambient magnetic fields. Therefore, the structure of MHD turbulence is closely related to the polarization observations. Assuming that dust grains are always aligned with their longer axes perpendicular to magnetic field (see the review Lazarian 2000), one gets the 2D distribution of the magnetic field directions in the sky. Note that the alignment is a highly non-linear process in terms of the magnetic field and therefore the magnetic field strength is not available<sup>11</sup>.

The statistics of starlight polarization (see FLPT) is rather rich for the Galactic plane and it allows to establish the spectrum<sup>12</sup>  $C_l \sim l^{-1.5}$ , where  $l$  is the multipole moment (see footnote 10). For uniformly sampled turbulence it follows from Lazarian & Shutenkov (1990) that  $C_l \sim l^\alpha$  for  $l < l_0$  and  $l^{-1}$  for  $l > l_0$ , where  $180^\circ/l_0$  is the critical angular size of fluctuations which is proportional to the ratio of the injection energy scale to the size of the turbulent system along the line of sight. For Kolmogorov turbulence  $\alpha = -11/3$ .

However, the real observations do not uniformly sample turbulence. Many more close stars are present compared to the distant ones. Thus the intermediate slopes are expected. Indeed, Cho & Lazarian (2002b) showed through direct simulations that the slope obtained in FLPT (2002) is compatible with the underlying Kolmogorov turbulence. At the moment FIR polarimetry does not provide maps that are really suitable to study turbulence statistics. This should change soon when polarimetry becomes possible using the airborne SOFIA observatory. A better understanding of grain alignment (see Lazarian 2000) is required to interpret the molecular cloud magnetic data where some of the dust is known not to be aligned (see Lazarian, Goodman, & Myers 1997 and references therein).

Another way to get magnetic field statistics is to use synchrotron emission. Both polarization and intensity data can be used. The angular correlation of polarization data (Baccigalupi et al. 2001) shows the power-law spectrum  $l^{-1.8}$  and we believe that the interpretation of it is similar to that of starlight polarization. Indeed, Faraday depolarization limits the depth of the sampled region. The intensity fluctuations were studied in Lazarian & Shutenkov (1990) with rather poor initial data and the results were inconclusive. Cho & Lazarian (2002b) interpreted the fluctuations of synchrotron emissivity (Giardino et al. 2001, 2002) in terms of turbulence with Kolmogorov spectrum.

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<sup>11</sup> The exception to this may be the alignment of small grains which can be revealed by microwave and UV polarimetry (Lazarian 2000).

<sup>12</sup> Earlier papers dealt with much poorer samples (see Kaplan & Pickelner 1970) and they did not reveal power-law spectra.

## 7 Summary

The principal points discussed above are as follows:

- Grain alignment theory has at last reached its mature state when predictions for classical ( $a > 3 \times 10^7$  cm) grains are possible. In most cases grain alignment happens in respect to magnetic field, i.e. reveal magnetic field direction, even if the alignment mechanism is not magnetic. However, depending on the mechanism the alignment may happen with grain longer axes parallel or perpendicular to magnetic field.
- “Resonance paramagnetic relaxation” is the process that can enable alignment and therefore polarization from ultrasmall grains. Although the details of the process still require laboratory testing, it looks that the polarization is marginal beyond 40 GHz. This process requires further work.
- Magneto-dipole emission may be substantially polarized in the range 10-90 GHz. Thus it can be important in terms of polarization even if it is subdominant in terms of total emissivity.
- Statistics of the galactic foreground polarization may be interpreted in terms of underlying MHD turbulence.

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